Renewable and Sustainable Energy Reviews 15 (2011) 2684–2689

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment methods of carbon dioxide emitted from bioenergy utilization

Yang Jing, Zhang Peidong*

Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences, Qingdao 266101, China

ARTICLE INFO

Article history:
Received 13 December 2010
Accepted 20 February 2011

Keywords:
Bioenergy
Carbon dioxide
Assessment method
Emission value

ABSTRACT

Renewability and cleanliness of bioenergy make itself one significant substitute of fossil energy. Estimate of carbon dioxide emission from bioenergy utilization is one of the basic steps to scientifically understand and evaluate the contribution of carbon dioxide emitted from bioenergy utilization. In this study, calculation methods of carbon dioxide emission from bioenergy utilization were summarized from the perspective of resources and utilization, mainly including five approaches: practical measurement method, material balance method, empirical coefficient estimation method, model method and life cycle assessment method. Valuable references for estimating carbon dioxide emission were provided and a series of feasible recommendations were also proposed for future use of bioenergy on the bases of analyzing advantages and disadvantages of each method and comparing them with methods used for fossil energy.

Contents

1. Introduction

Since the 80s of the 21st century, the world has attached great importance to the R&D on technologies and utilizations of bioenergy [1]. On policy, many countries have issued relevant strategies to dedicatedly support development of bioenergy, such as Ameri-

* Corresponding author.
E-mail address: eeesc@163.com (P. Zhang).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.02.028

can "Energy farm plan", Brazilian "Alcohol energy plan", Japanese "solar beam plan" and Indian "Green Energy Engineering" and so on [2–5]. In some countries, researches and utilizations of bioenergy have been advocated and protected in the form of legislation. Germany has enacted Renewable Energy Law in 2000. Brazil has been protecting bio-ethanol by legislation since implementation of bio-ethanol program. U.S. Congress has passed Biomass Research and Development Bill in 2000. And Malaysia has included forced sale of biodiesel into proposed Biofuel Act [6–8]. Bioenergy researches started lately in China. However, bioenergy such as bio-ethanol, biodiesel and biomass pellet fuels are now growing rapidly after years of development [9].

As research in bioenergy develops, the understanding of the relationship between bioenergy and environment becomes more and more rational and objective. It is reported that bioenergy is not always absolutely beneficial to environment. Expanding utilization of bioenergy can lead to change in land use and increase of carbon emissions from the terrestrial eco-system [10]. Biofuels can be carbon neutral, carbon negative, or carbon sources, depending on both how much CO_2 and other greenhouse gases, expressed as CO_2 equivalents, are removed from or released into the atmosphere during crop growth and how much fossil CO_2 is released in biofuel production [11]. In a world seeking solutions to its energy, environment, and food challenges, society cannot afford to miss out on the global greenhouse-gas emission reductions and the local environmental and societal benefits when biofuels are done right. However, society also cannot accept the undesirable impacts of biofuels done wrong [12]. Biofuels are low-carbon energy source for potential, but whether biofuels offer carbon reduction depends on how they are produced and applied. Some research has concluded that the net effect of biofuels production via clearing of carbon-rich habitats was to increase CO_2 emissions for decades or centuries. Conversely, biofuels produced from waste biomass and from perennials plants on degraded cropland could minimize the issues like habitat destruction, competition with food production and carbon debts, all of which were associated with direct and indirect land clearing for biofuels production [13]. From the perspectives of energy, environment and social sustainability, it is essential not only to figure down the qualitative relation between bioenergy utilization and carbon dioxide emission, but also to quantify the relationship.

2. Bioenergy utilization and carbon dioxide emission

Compared to fossil energy, bioenergy is often highlighted for its merit of environment friendly. Carbon neutral, frequently mentioned in bioenergy use, means that carbon dioxide emitted from bioenergy utilization is compensated by planting to reach the purpose of environmental protection, without aggravating greenhouse effect. Emission of carbon dioxide from bioenergy consumption is almost equivalent to the amount of that absorbed by plants from atmosphere through photosynthesis during their growth [14]. Conclusion of "balance of absorption and emission" of carbon dioxide can be obtained on the base of substance balance of biomass. However, there is no doubt that utilization of bioenergy affects atmospheric carbon flow cycle, the regional carbon source and sink. Additional energy input (usually fossil energy) to bioenergy production also affects on carbon dioxide emission. From an environmentally sustainable perspective, it is blind to simply identify bioenergy as zero emission of pollutants.

2.1. Study objectives

Objectives of this study are to summarize the methods of estimating carbon dioxide emissions from bioenergy utilization, and to compare their advantages and drawbacks in order to find out applicable solutions. Results of this study are supposed to provide essential preparations for assessment of bioenergy use and valuable references for reduction of greenhouse gas. Also, some feasible recommendations are put forward for future researches on the base of discussion on available methods.

2.2. Study scope

Biomass used as a kind of energy has its own life cycle which can be divided into several units of production, utilization and disposal, while carbon dioxide emissions may exist in each of them. The objects investigated in this study are calculation methods of carbon dioxide emission from bioenergy utilization. The scope of this study is limited to the field of biomass used as energy.

3. Domestic and international research progresses

3.1. Biomass resources

3.1.1. Forest biomass and carbon dioxide emission

Forest biomass takes up a large proportion of biomass resources. However, to date, used as energy, it mainly includes a variety of forest waste and firewood forest.

For bioenergy system using logging waste as the feedstock, Schlamadinger et al. introduced the concept of Carbon Neutrality to provide a useful, time-dependent measure of the extent to which an alternate energy system yields a net reduction in CO_2 emissions, and built a model to assess the carbon balance for the whole system [15]. As to forestry projects, a computer model of carbon pools and fluxes was employed to calculate carbon balances of two land management and biomass utilization scenarios-conventional forest management and short-rotation forestry [16]. Paul et al. estimated net CO_2 emissions for three contrasting systems producing firewood for domestic heating: (i) woodland; (ii) native forest harvested for wood production; and (iii) a newly established plantation in Australia, applying the FullCAM model and additional calculations to account for changes in C stocks (and the equivalent CO_2 emission) within living biomass, debris and wood products. Emissions of CO_2 associated with the establishment, harvesting and transport were estimated separately. The net amount of CO_2 emitted (as a result of changes in stocks of C as well as the use of diesel fuel) for per unit of energy generated from burning of firewood was termed the conversion factor [17].

On the base of appraisal and analysis of currently existing amount of biomass resources in China, Li summarized the method for calculating reduction of carbon dioxide based upon substituting fossil fuel for forest biomass. It was considered that the direct effects of forest biomass on reduction of carbon dioxide consisted of three parts. The calculation formula as follows:

$$Q = \sum C_t + \sum C_x - \sum C_{sh}, \tag{1}$$

where C_t was emission reduction caused by substituting fossil fuel for biofuel, which could be obtained by applying the biomass computing model for terrestrial ecosystem and multiple methods validated by field research; C_x means absorptive amount of carbon dioxide during their growth, which was approximately zero; and C_{sh} was carbon dioxide emission derived from fossil fuel input for forest production, which was calculated using equation (2).

$$Q = q \times a \times b \times c, \tag{2}$$

where Q was the total reduction of carbon dioxide; q was application amount of forest biomass; a was transfer coefficient for fossil energy (0.67); b was emission factor for standard coal (2.13); c was conversion coefficient for reduction of carbon dioxide (<1) [14].

Both forest management and biomass fuels were mentioned as offering possibilities to reduce net emissions of CO_2 in the research of Marland and Schlamadinger [18]. Based on the assumption of focusing only on the most importance of the greenhouse gases, CO_2, a mathematical model GORCAM (Graz/Oak Ridge Carbon Accounting Model) [19] was applied to examine carbon flows for different forest management/biomass energy scenarios in order to assess the greenhouse effect on the integrated bioenergy system.

3.1.2. Cultivation of biomass crops and carbon dioxide emission

Bioenergy crops offset carbon dioxide emissions by converting atmospheric CO_2 to organic C in crop biomass and soil. Adler determined net effect of several bioenergy cropping systems on greenhouse-gas (GHG) emissions. The DAYCENT biogeochemistry model was used to assess soil GHG fluxes and biomass yields for corn, soybean, alfalfa, hybrid poplar, reed canarygrass, and switchgrass as bioenergy crops in Pennsylvania, USA. The results were combined with estimates of fossil fuels used to provide farm inputs and operate agricultural machinery and fossil-fuel offsets from biomass yields to calculate net GHG fluxes [20]. Hughes et al. integrated a process-based model of the energy crop miscanthus giganteus into the global climate impact model IMOGEN, simulating the potential of large-scale miscanthus plantation to offset fossil fuel emissions. Effect of cultivating bioenergy crops was measured by "pay-back time" [21].

A life cycle assessment for integrated cultivation system of bioenergy crop has been conducted by Fukushima and Chen. Calculation of direct emissions in this category was carried out following the guidelines issued by the Intergovernmental Panel on Climate Change (IPCC) described in Eqs. (3) and (4).

$$E_{\mathrm{df}} = Q_{\mathrm{fossil}} \times EF_{\mathrm{fossil}} \tag{3}$$

$$E_{\mathrm{dc}} = E_{\mathrm{farm}} - E_{\mathrm{fallow}}, \tag{4}$$

where E_{dc} was direct emissions of CO_2, CH_4 and N_2O from soil in the cropping cycles, kg; E_{df} was direct emissions of CO_2, CH_4 and N_2O from fossil fuel combustion, kg; E_{fallow}: emission from soil under the fallow land conditions, kg; E_{farm} was emission from soil under the sugarcane farm conditions, kg; EF_{fossil} was emission factor of fossil diesel, kg/TJ; Q_{fossil} was the quantity of fossil diesel consumed, TJ.

Emissions from power generation, chemical manufacturing and fossil diesel refining, which were classified as indirect emissions were calculated using two empirical formulas [22]:

$$E_{\mathrm{p}} = Q_{\mathrm{p}} \times EF_{\mathrm{p}} \tag{5}$$

$$E_{\mathrm{c}} = Q_{\mathrm{c}} \times \phi_{\mathrm{c}}, \tag{6}$$

where E_{c} was GHG emission inventories of chemicals and fossil diesel, kg-CO_2-equiv.; E_{p} was GHG directly emitted from power generation, kg-CO_2-equiv.; EF_{P} was GHG emission factor of electricity, kg-CO_2-equiv./kWh; φ_{c} was GHG emission inventory of chemicals and fossil diesel, kg-CO_2-equiv./kg or kL; Q_{c} was chemicals and fossil diesel used, kg or kL; Q_{p} was electricity generated, kWh.

3.2. Production and utilization of biofuels

3.2.1. Biomass liquid fuels and carbon dioxide emission

Biodiesel treated as one substitution of fossil fuel, has great advantages over conventional diesel, especially with outstanding merit in reduction of carbon dioxide. The main component of biodiesel is fatty acid methyl ester or fatty acid ethyl ester. Biodiesel, either pure oil or in various proportions with conventional diesel to hybrid, plays a positive role in carbon dioxide reduction. The American Department of Energy's research concluded that it would reduce carbon dioxide emission by 15.6% and 78.4% using B20 (biodiesel combined with conventional diesel by 1:4) and B100 (pure biodiesel) respectively, compared with purely using conventional diesel, from the perspective of fuels' life cycle [23]. For different feedstocks, Hu et al. established a life cycle energy consumption and emission model to assess biodiesel, results of which showed that life cycle fossil energy consumption of diesel derived from any feedstock significantly decreased, as well as life cycle carbon dioxide emission [24]. Coronado et al. considered that calculation of carbon dioxide emission could be determined by its emission factors dependent on combustion. Taking density of feedstock into account, relevant chemical combustion equations were derived to compute the emission of carbon dioxide [25].

There were also several researches focusing on carbon reduction contributed by bio-methanol application. Kristiina presented a method of calculating carbon emissions avoided by converting biomass to methanol and using it as a transportation fuel or to produce electricity. Under the efficiencies of methanol production at the range of 25–50%, the amount of carbon emissions avoided was estimated by determining the amount of energy produced, or electricity derived, from 1 mg of biomass that could replace or substitute for an equivalent amount of energy produced from non-renewable resources, such as natural gas, gasoline, or other fossil-fuel derived products [26].

According to a research reported by McKinsey in 2009, there would be 31 million tons of gasoline displaced by bio-ethanol, as a result of which China's foreign dependence of oil would reduced by 10%, and the amount of carbon dioxide reduction would reach 90 million tons per year [27]. Compared to other bioenergy industries, bio-ethanol has developed more rapidly and achieved more success. And there have been a number of literatures associated with environmental benefit of bio-ethanol on a life cycle base. Kadam built a life cycle assessment (LCA) model to simulate biomass-based CO_2 emissions, applying the TEAM software [28]. Hu et al. investigated how to calculate carbon dioxide emission while assessing cassava-based ethanol (CE) in China. By the means of developing a computer-based Excel spreadsheets model, the energy consumption, CO_2 emissions and cost during the path of the CE's life cycle, were calculated. The CO_2 emission from a fuel, GCE, was the "gross" of CO_2 emissions, which included the direct (combustion) and indirect (feedstock and fuel) CO_2 emissions. Here, $GCE = CE_1 + CE_2 + CE_3$, where CE_1, CE_2, and CE_3 represented CO_2 emissions during the stages of feedstock, fuel, and fuel combustion respectively [29].

Blottnitz and Curran analyzed a set of literatures published from 1996 to 2004, in association with assessments of bio-ethanol used as translation fuel, involving carbon accounting which applied computing formula of carbon dioxide equivalent [30]:

$$C_{\mathrm{eq.emm.}} = \frac{44}{12}(C_{\mathrm{A}} + C_{\mathrm{B}} + C_{\mathrm{C}} + C_{\mathrm{D}}) + \sum_{j} GWP_j \left[\sum_{i=a}^{e} X_{ij} \right] \tag{7}$$

Lave et al. appraised the life cycle economic and environmental benefit of automotive fuel, including calculation of carbon dioxide emitted from biofuel utilization from a life-cycle perspective. The life-cycle analysis originated from two sources: one was Environmental Input–Output Life-Cycle Analysis software (EIO-LCA), the other was process model studies designed to provide these disaggregate data [31]. Su and Lee applied life cycle assessment (LCA) procedures outlined in ISO14040:2006 to construct the inventory of inputs of energy and materials as well as outputs of pollutant and carbon dioxide emissions only for the use of diesel consumed by the harvest machines [32].

Bergsma et al. [33], the developers of a life-cycle-based GHG indicator (also known as a CO_2 tool or carbon footprint) stated in their report that life-cycle assessment (LCA), as described in the ISO standards had been adopted for the calculation of this indicator.

The basic formula of estimating percentage of GHG reduction achieved by a particular biomass production chain was as follows:

$$GHG_{\text{reduction}}(\%) = \frac{GHG_{\text{emission,fossilchain}} - GHG_{\text{emission,biochain}}}{GHG_{\text{emission,fossilchain}}} \times 100 \tag{8}$$

However, the ISO standard had not discussed what type of LCA methodology would be best to address the topic of bioenergy versus fossil energy. Guinée et al. provided a discussion of this issue to illustrate the possible effect on the GHG indicator [34].

3.2.2. Biogas utilization and carbon dioxide emission

Biogas is often advocated as a significant contributor to possible solutions to carbon dioxide emission.

As for medium-sized biogas project, calculation method of carbon dioxide reduction was on the base of a complete life cycle of the whole project, including emissions from both production and utilization [35].

Wang [36] and Zhang et al. [37,38] estimated carbon dioxide emissions from both biofuel and biogas combustion, applying empirical equation on the base of industrial emission factors. Liu and Kuang who followed the calculation method recommended by IPCC estimated the energy saved and GHG reduction as a result of biogas utilization in order to analyze the total reduction of GHG emission in each provinces and autonomous regions in China and to predict the further reduction of GHG [39]. From the point of energy consumption substitute, Liu established an environmental accounting equation for energy GHG reduction to assess the annual reduction benefit of each marsh gas tank, applying the default emission factor published by IPCC [40].

3.2.3. Straw utilization and carbon dioxide emission

Technologies applied in straw utilization primarily include direct combustion technology, pyrolytic technology, gasification technology and bio-conversation technology [41]. To date, practical utilization of straw mostly centered on direct combustion, while for researches, much more attentions were paid to straw power generation. However, focus on straw research has seldomly converted to calculation of carbon dioxide emission.

Shi et al. calculated the integrated energy efficiency and the greenhouse effect of the system under life cycle assessment, taking the case of maize straw gasification system of synthesis of dimethyl ether, which has a production capacity of 1000 t/a. The evaluation result indicated that carbon dioxide fixed in maize straw was 77% of that emitted from production and utilization of dimethyl ether, which had obviously benefited to GHG reduction [42].

3.2.4. Biomass briquette and carbon dioxide

Biomass briquette is also receiving more and more attention as bioenergy develops. In order to estimate greenhouse gas emissions from fuel chip production, Wihersaari built an accounting model, results of which showed that emissions from collecting, chipping and transporting the residues were evaluated to be about 4–7 kg CO_2 eqMWh$^{-1}{}_{\text{chip}}$ depending on harvesting and chipping methods and transportation distance [43].

Bio-char (biologically derived charcoal), as one kind of biomass products, possessed great potential to enhance natural rates of carbon sequestration in soils, reduce farm waste, and substitute renewable energy sources for fossil-derived fuel inputs. Net reduction of carbon dioxide from atmosphere was obviously one of its environmental benefits [44].

3.2.5. Biomass power generation and carbon dioxide emission

Concerning to biomass power generation, much research and development (R&D) have been conducted to biomass pyrolysis gasification technique in many countries. Finnish Tam Perret Power Company has started to establish a waste wood gasification power plant, while Swedish Energy Center has planned to build a power plant based on biomass gasification and combined cycle power generation technique to dispose of abundant local bagasse. In America, more than 350 biomass power generation plants have been built [45].

Liang and Fan quantified the carbon dioxide emission from fire coal by determining consumption of coal in thermal power generation substituted by renewable energy. The net reduction of carbon dioxide was calculated by the following formula:

$$\Delta EM = G \times a \times EM_{\text{b}} \tag{9}$$

where ΔEM meant net reduction of carbon dioxide; G was annual electrical quantity generated by renewable energy; a was standard coal consumption per unit in coal-fired power plant; EM_{b} was emission factor of carbon dioxide for standard power generation technique [46].

Yang and Ma calculated the net reduction of carbon dioxide using UNFCCC's accounting formula from uniform baseline methodology of the approved landfill gas project. The benefit of GHG reduction in landfill gas power generation was also analyzed in their studies [47]. More attentions should be paid to bioenergy to reduce the reliance on limited fossil energy for three sectors including heat, power and transportation fuels, which were all considered as big energy consumers. Schmidt et al. presented a spatial explicit optimized model to assess the impact of carbon dioxide reduction in these sectors. The model tracked CO_2 emissions from bioenergy production as well as CO_2 emissions from fossil fuel combustions. A MIP model used to minimize the costs for supplying demand regions with different forms of energy products from either biomass plants or fossil fuels involved estimate of carbon dioxide reduction by following equation [48]:

$$totem = \sum_{i,j,l} e_{i,j}^{\text{trans}} b_{i,j,l} + \sum_{k,c} e_c^{\text{fossil}} z_{k,c}^{\text{fossil}} + \sum_{h,t} e_h^{\text{local}} q_{h,t}^{\text{local}} + \sum_{h,t} e_{h,t}^{\text{peak}} q_{h,t}^{\text{peak}} - \sum_{i,j,l} e_l^{\text{ccs}} b_{i,j,l}, \tag{10}$$

where $totem$ was total CO_2 emissions; $\sum_{i,j,l} e_{i,j}^{\text{trans}} b_{i,j,l}$ were CO_2 emissions of biomass transportation (CO_2 emission factor $e_{i,j}^{\text{trans}}$); $\sum_{k,c} e_c^{\text{fossil}} z_{k,c}^{\text{fossil}}$ were CO_2 emissions of commodity transportation (CO_2 emission factor $e_{j,k,c}^{\text{trans}}$); $\sum_{h,t} e_h^{\text{local}} q_{h,t}^{\text{local}}$ were CO_2 emissions of fossil energy production (CO_2 emission factor $e_{j,k,c}^{\text{trans}}$); $\sum_{h,t} e_h^{\text{local}} q_{h,t}^{\text{local}}$ were CO_2 emissions of local heating systems(CO_2 emission factor e_c^{fossil}); $\sum_{h,t} e_{h,t}^{\text{peak}} q_{h,t}^{\text{peak}}$ were CO_2 emissions of peak heat production (CO_2 emission factor $e_{h,t}^{\text{peak}}$).

4. Conclusions obtained from relevant studies

4.1. Sources of carbon dioxide

Energy contained in biomass is converted from photosynthesis of plants, but biomass is not the only participant of life cycle process of bioenergy utilization. Carbon dioxide emitted from utilization process of a variety of bioenergy systems should not only include carbon dioxide converted from its own carbon element in biomass, but also include that converted from additional energy input, for example, fossil fuel input for transportation of raw materials and other energy input in processing and transformation of biomass.

4.2. Primary calculation methods

Similar to fossil fuels, carbon dioxide emitted from the process of bioenergy use, can be calculated in the following five methods:

Table 1
Merits and drawbacks of some methods used in estimate of carbon dioxide emission from bioenergy utilization.

	Merits	Drawbacks
Practical measurement method	High accuracy in continuous monitoring	High cost in single continuous monitoring
Material balance method	Lower require in data, simple calculation	Lower accuracy
Empirical coefficient estimation method	Better applicability in lack of statistical data	Results with great uncertainty
Model method	Systematic and detailed	Without targeted and unified calculation models
Life cycle assessment method	"Cradle to grave", comprehensive consideration on environmental sustainability	Complicated calculation

practical measurement method, material balance method, empirical coefficient estimation method, model method and life cycle assessment method.

Practical measurement method which means direct measurement needs essential base installation to obtain sample data according to a lot of testing or continuous monitoring. People responsible for the measurement have to be expert enough to ensure the accuracy. Actually, this method is rarely used to obtain the data of carbon dioxide emission in bioenergy use.

Material balance method is actually a method in association with calculation of material quality. When all the input/output efficiencies are determined accurately, emission efficiency of pollutant can also be exactly determined. The basic emission estimation equation of material quality is as follows:

$$E_t = (M_{in} - M_{out}) \times C, \tag{11}$$

where E_t is the total emissions of pollutants; M_{in} means substances into the production process; M_{out} means substance out of the production process in the form of waste, recycling materials or products; C means concentration of pollutants in substances.

On the base of above accounting, the conclusion of zero emissions of carbon dioxide from biomass can be conducted.

However, as a result of additional energy input into the processes of production, transportation and utilization of bioenergy, estimates are usually conducted at the premise of certain assumptions and simplification, and do not necessarily demonstrate to be zero.

Calculation of emission in the way of empirical coefficient estimation method is deduced on the base of empirical formulas, which involves emission factors of a variety of sectors respectively. Definition of these factors is of the utmost importance to accuracy of the estimate. For example, emission factors recommended by IPCC were applied in estimate of carbon dioxide emitted from biogas utilization by Liu et al. [39] and Liu [40]; empirical equations were used to calculate related emissions in biomass combustion and biogas combustion by Wang [36] and Zhang [37,38].

Model is commonly found in researches of bioenergy, either for technique studies or assessment researches, for example, FullCAM model used by Paul et al. [17]; GORCAM (Graz/Oak Ridge carbon accounting model) applied by Marland and Schlamadmger [19]; respective Models in researches of Adler et al. [20] and Hughes et al. [21]; MIP model involved in Schmidt's [48] study. Estimate of carbon dioxide was always involved as one part of the integrated assessment models.

With regard to either source utilization or environmental benefit, life cycle assessment method is undoubtedly a good method for its comprehensive and detailed nature. So far, there have been many researches introducing this method to assess the integrated effects of energy and environment, such as, life cycle inventory analysis on biofuel in Taiwan [32]; Bergsma's [33] life cycle analysis and the improved method developed by Guinée et al. [34]; the case of life cycle assessment in Shi's [42] research. However, there have been much less concern conducted to assessment simply for life cycle emission of carbon dioxide.

Table 2
Contrasts of bioenergy and fossil energy in estimating methods of carbon dioxide emission.

Bioenergy	Fossil energy
Practical measurement method	Sampling or direct measurement
Material balance method	Material balance method
Empirical coefficient estimation method	Emission factors method
Model method	Engineering calculation-fuel analysis
Life cycle assessment method	Engineering assessment

4.3. Contrast of methods

With constrain of measurement, economy and objective environment conditions, calculation methods of carbon dioxide emission from each technique process and the whole life cycle of its utilization are of great differences, and have each own advantages and disadvantages, as shown in Table 1.

4.4. Methods comparison with CO_2 emission used by fossil energy

For quite a long time, the field of world's energy was dominated by fossil energy which at the same time also played a significant role in emission of GHG. The methods of calculating carbon dioxide emission from fossil fuel have developed to be more mature compared to those of bioenergy. Contrasts of the two are as Table 2:

5. Discussion and suggestions

One truth can be easily found according to the analysis of both domestic and international studies on estimate of carbon dioxide emission from bioenergy utilization. It is that, to date, dedicated research on emission estimate is relatively less and incomplete.

(1) Assessment associated with bioenergy utilization was mostly conducted on integrated environmental or economic benefit, compared to fossil energy. However, assessment for estimate of carbon dioxide emission was not the main content but usually acted as one aspect involved.
(2) Different to fossil energy, bioenergy comes from various sources and converted to a variety kinds of products according to different technologies. So, processes of both production and utilization were found to be complicated. Calculations of carbon dioxide emission mainly depended on specific production application models or applied empirical equations without standard computation methods. Formulas in common use for calculation were mostly derived from fossil energy or other industrial sectors.
(3) Estimate of carbon dioxide emission from bioenergy utilization was often accompanied with assessment of certain technical process. There were fewer studies on assessment of integrated bioenergy system on its life cycle perspective, and corresponding assessment on environmental benefit developed incompletely because technologies in different bioenergy have not kept in the same step. For example, estimate of emission

from more developed bio-ethanol received more attention on its assessment, while less developed biodiesel received less focus on its environmental assessment.

To address the above shortcomings, some recommendations on calculation of carbon dioxide emission from bioenergy are proposed. Research on methodology of calculating carbon dioxide emission from bioenergy utilization should be enhanced in order to format a set of systematic methods for all kinds of bioenergy systems and different processes of bioenergy utilization. More efforts should be made to analysis the benefit of carbon dioxide reduction from the point of life cycle assessment, breaking the limitation of considering only on part of factors correlative to estimate of carbon dioxide without overall consideration. Single evaluation method is not always applicable for every process of the whole system. Thus, more researches need be to done in an effort to select appropriate estimate methods for different processes and finally to assess carbon dioxide emission on the base of life cycle consideration of both general economic condition and objective environment constraint.

Acknowledgements

The authors would like to thank National Natural Science Foundation of China for the continued assistance. Research of this study has been supported by State Natural Sciences Foundation Projects (40901063).

References

[1] Tang HY, Hu YJ. Overview of international bio-energy industry development. World Forestry Research 2008;21(3):72–4.
[2] Wang L. Present situation and prospects of bioenergy. China Chemicals 2009;2:48–50.
[3] Fei SM, Zhang XD, Yang GY, Zhou JX, Liu FY. On domestic and international situation of energy plant resources and their exploitation. Journal of Sichuan Forestry Science and Technology 2009;2:48–50.
[4] Jiang M, Wei P, Lu DQ, Xv H, Zhou H, Ouyang PK. Considerations on the development of industrial biotechnology of post-petroleum epoch. Chemical Industry and Engineering Progress 2006;25(10):1119–23.
[5] Wu PF, Ma XQ, Wang P. Potential and countermeasures of the development of the raw material forest of biological energy plant in China. Subtropical Agriculture Research 2007;3(2):125–8.
[6] Xu DQ. World's renewable energy development and policy orientation in China. Sea of Learning 2009;6(6):69–72.
[7] Liu N, Zhang ZF. International supporting policies for biomass energy industry. World Forestry Research 2009;22(1):77–80.
[8] Li BF. Study on impact of the biofuel development on food security and energy security. Ecological Economy 2010;222:41–2.
[9] Chen ZZ. Research progress of bio-energy. Chemical Intermediates 2009;(1):1–4.
[10] Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, Fabiosa J, et al. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 2008;319:1238–40.
[11] Tilman D, Hill J, Lehman C. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 2006;314:1598–600.
[12] Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, et al. Beneficial biofuels—the food, energy, and environment trilemma. Science 2009;325:270–1.
[13] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319(5867):1235–8.
[14] Li SL, Wang YH, Song WM. Function of developing forest biomass energy on reducing carbon dioxide. Journal of Northeast Forestry University 2009;37(4):83–5.
[15] Schlamadinger B, Spitzer J, Kohlmale GH, Lüdeke M. Carbon balance of bioenergy from logging residues. Biomass and Bioenergy 1995;8(4): 221–34.
[16] Schlamadinger B, Marland G. Full fuel cycle carbon balances of bioenergy and forestry options. Energy Conservation 1996;37(6–8):813–8.
[17] Paul KI, Booth TH, Elliott A, Kirschbaumc MUF, Jovanovica T, Polglase PJ. Net carbon dioxide emissions from alternative firewood-production systems in Australia. Biomass and Bioenergy 2006;30:638–47.
[18] Marland G, Schlamadinger B. Biomass fuels and forest-management strategies-How do we calculate the greenhouse-gas emissions benefits. Energy 1995;20(11):1131–40.
[19] Schlamadmger B, Marland G. The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy 1996;10(5/6):275–300.
[20] Adler PR, Del Grosso SJ, Parton W. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications 2007;17(3):675–91.
[21] Hughes JK, Lloyd AJ, Huntingford C, Finch JW, Harding RJ. The impact of extensive planting of Miscanthus as an energy crop on future CO_2 atmospheric concentrations. GCB Bioenergy 2010;2:79–88.
[22] Fukushima Y, Chen SP. A decision support tool for modifications in crop cultivation method based on life cycle assessment: a case study on greenhouse gas emission reduction in Taiwanese sugarcane cultivation. International Journal of Life Cycle Assessment 2009;14(7):639–55.
[23] John SH, Vince CB. An overview of biodiesel and petroleum diesel life cycles. National Renewable Energy Laboratory; 1998.
[24] Hu ZY, Tan PQ, Lou DM, Dong YQ. Assessment of life cycle energy consumption and emissions for several kinds of feedstock based biodiesel. Transactions of the CSAE 2006;22(11):141–6.
[25] Coronado CR, de Carvalho JA, Silveira JL. Biodiesel CO_2 emissions: a comparison with the main fuels in the Brazilian market. Fuel Processing Technology 2009;90(2):204–11.
[26] Vogt KA, Vogt DJ, Patel-Weynand T, Upadhye R, Edlund D, Edmonds RL, et al. Bio-methanol: how energy choices in the western United States can help mitigate global climate change. Renewable Energy 2009;34:233–41.
[27] Hao XM. Trend of the fuel ethanol industry in China. China Venture Capital 2010:51–2.
[28] Kadam KL. Environmental benefits on a life cycle basis of using bagasse-derived ethanol as a gasoline oxygenate in India. Energy Policy 2002;30(5):371–84.
[29] Hu ZY, Fang F, Ben DF, Pu GQ, Wang CT. Net energy, CO_2 emission, and life-cycle cost assessment of cassava-based ethanol as an alternative automotive fuel in China. Applied Energy 2004;78:247–56.
[30] Blottnitz HV, Curran MA. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. Journal of Cleaner Production 2007;15:607–19.
[31] Lave L, Maclean H, Hendrickson C, Lankey R. Life-cycle analysis of alternative automobile fuel propulsion technologies. Environmental Science and Technology 2000;34(17):3598–605.
[32] Su CL, Lee YM. Development status and life cycle inventory analysis of biofuels in Taiwan. Energy Policy 2009;37(2):754–8.
[33] Bergsma G, Vroonhof J, Dornburg V. The greenhouse gas calculation methodology for biomass-based electricity, heat and fuels—the view of the Cramer Commission. Delft, the Netherlands: CE Delft Solutions for Environment, Economy and Technology; 2006.
[34] Guinée JB, Heijungs R, der Voet EV. A greenhouse gas indicator for bioenergy: some theoretical issues with practical implications. International Journal of Life Cycle Assessment 2009;14:328–39.
[35] Su MS, He JK, Gu SH. Approach to estimate CO_2 reduction and increment cost for large biogas systems. China Biogas 2002;20(1):26–8.
[36] Wang GH. Analysis method on reducing emission of SO_2 and CO_2 by rural energy construction. Transactions of the CSAE 1999;15(1):169–72.
[37] Zhang PD, Wang G. Contribution to reduction of CO_2 and SO_2 emission by household biogas construction in rural China: analysis and prediction. Transactions of the CSAE 2005;21(12):147–215.
[38] Zhang PD, Li XR, Yang YL, Zheng YH, Wang LS. Greenhouse gas mitigation benefits of large and middle-scale biogas project in China. Transactions of the CSAE 2008;24(9):239–43.
[39] Liu Y, Kuang YQ, Huang NS. Rural biogas development and greenhouse gas emission mitigation. China Population, Resources and Environment 2008;18(3):48.
[40] Liu YZ. Environmental benefits evaluation of energy greenhouse gas emission reduction of using household biogas. Journal of Yangtze University (Nature Science Edition) 2009;6(1):81–4.
[41] Hu JM. Analysis of resources utilization on crop stalks. Guangdong Agriculture Science 2010;(4):207–10.
[42] Shi XG, Lei TZ, Wang ZW, Bai W, He XF, Yang SH, et al. Analysis of life cycle energy consumption and greenhouse gas emission of cornstalk-based dimethyl ether. Renewable Energy Resources 2009;27(3):60–4.
[43] Wihersaari M. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 2005;28(5):435–43.
[44] McHenry MP, Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: certainty, uncertainty and risk. Agriculture Ecosystems and Environment 2009;129(1–3):1–7.
[45] Cao L, Yi LZ, Sun J. The application status and prospect of biomass energy source in the fuel production and power generation. Pratacultural Science 2009;26(9):49–53.
[46] Liang YJ, Fan JC. The benefit of renewable energy power generation technologies to the reduction of the greenhouse gas emission. Renewable Energy 2004;113(1).
[47] Yang J, Ma XQ. The benefit of landfill gas power generation to the reduction of the greenhouse gas emission. Environmental Pollution and Control 2006;28(6):461–4.
[48] Schmidt J, Leduc S, Dotzauer E, Kindermann G, Schmid E. Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: a spatially explicit comparison of conversion technologies. Applied Energy 2010;87:2128–41.